Proceedings of ENCIT 2010
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13th Brazilian Congress of Thermal Sciences and Engineering
December 05-10, 2010, Uberlandia, MG, Brazil

EXERGY AND EXERGOECONOMIC ANALYSIS OF A PETROLEUM REFINERY UTILITIES PLANT USING THE CONDENSING TO POWER METHOD

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Abstract. In this paper a brief description of the main processes present in a modern high capacity refinery is made. It presents the methodology used to evaluate, through exergy analysis, the performance of the refinery's utilities plant since it is responsible for a very considerable amount of the total exergy destruction in a refinery. The utilities plant products: steam, electricity, shaft power and high pressure water had their exergy unit cost determined using exergoeconomic approach. A simple and effective method called condensing to power was used to define the product of the condensers in exergy basis. Using this method it is possible to define the product of the condenser without the use of negentropy concept nor the aggregation of condensers to the steam turbines. By using this new approach, the costs obtained for the plant's products are exactly the same costs obtained when the condenser is aggregated to the steam turbine but with the advantage that the information about the stream between condenser and the steam turbine is not lost and the condenser can be evaluated singly. The analysis shows that the equipments where attention and resources should be focused are the boilers followed by the gas turbine, that together, are responsible for 80% of total exergy destruction in the utilities plant. The total exergy efficiency found for the utilities plant studied is 35% while more than 280 MW of exergy is destructed in the utilities processes.

Keywords: *Exergy Analysis, Exergoeconomic Analysis, Power Plant, Utilities Plant, Petroleum Refinery.*

1. INTRODUCTION

According to data from DOE/EIA (2010) there will be an increment of 29% and 38% in the next 25 years in the use of liquids derived from petroleum and natural gas respectively as energy resources in the world. In Brazil, according to EPE (2009), the oil production will increase from 2 million of barrels per day (bpd) to 5.1 million bpd in the next 10 years. In this scenario of increasing use of fossil fuels, process efficiencies play an important role keeping the Green House Gas (GHG) emissions at acceptable levels and to reduce the amount of potential work that is destructed in the energy conversion processes.

In this work, the utilities plant of a modern high capacity refinery (360.000 bpd) is analyzed using the First and Second Laws of Thermodynamics as tools (exergy analysis) to locate components responsible for the major exergy destruction. Furthermore, a refinery is a typical application for thermoeconomics, since it is composed by several internal units that exchange heat, work, fuels and matter between themselves in order to produce several final products, making the production cost allocation for each internal unit a difficult task. Thus, in this paper the production costs, expressed in exergy basis, of utilities plant were distributed to the real streams using the exergy of the flows as weighting factor and also using a simple and effective approach to define the condensers exergy product. This work is a part of an ongoing project that aims at developing an exergy and exergoeconomic analysis of a whole refining process.

2. REFINING PROCESSES

After the primary separation and treatment the petroleum is split into streams of natural gas, crude oil with acceptable levels of water and sediments (BSW) and water that is disposed or re-injected in the well. Natural gas goes to the processing units to adequate it for commercial use whist the crude oil goes into the refining process to generate products with higher commercial value. The refining scheme varies according to the crude oil characteristics and desired products. The analyzed refinery is composed by an atmospheric distillation unit that receives heated crude oil, after pass through the furnace and heat exchangers network, and supplies different products: liquefied petroleum gas (LPG), light and heavy naphtha, kerosene and light and heavy diesel. The residue of atmospheric distillation is fed to the vacuum distillation unit that produces: gasoil, fuel oil and asphalt. The residue of vacuum distillation is sent to coking unit that will produce LPG, naphtha and gas oil. The produced gasoil is used as charge in the fluid catalytic cracking unit (FCC) to produce more naphtha and LPG. Thus, it is possible to maximize the production of naphtha and LPG. Before their commercialization, products need some treatment to adequate them to the market requirements and to avoid corrosion problems during transportation and storage. The main treatments used are hydrotreatment and caustic treatment, which is used to remove the sulfur and others contaminants. These units exchange heat, work, electricity and matter between themselves while the utility plant has to provide steam at 3 different pressure levels, electricity, mechanical shaft work and high and low pressure water, consuming for this purpose fuel gas, fuel oil and CO (carbon monoxide) gas provided by the others units. Besides that, the utility plant also consumes natural gas from outside. Fig. 1 shows the simplified refining scheme of the analyzed refinery and the interaction with utilities plant.

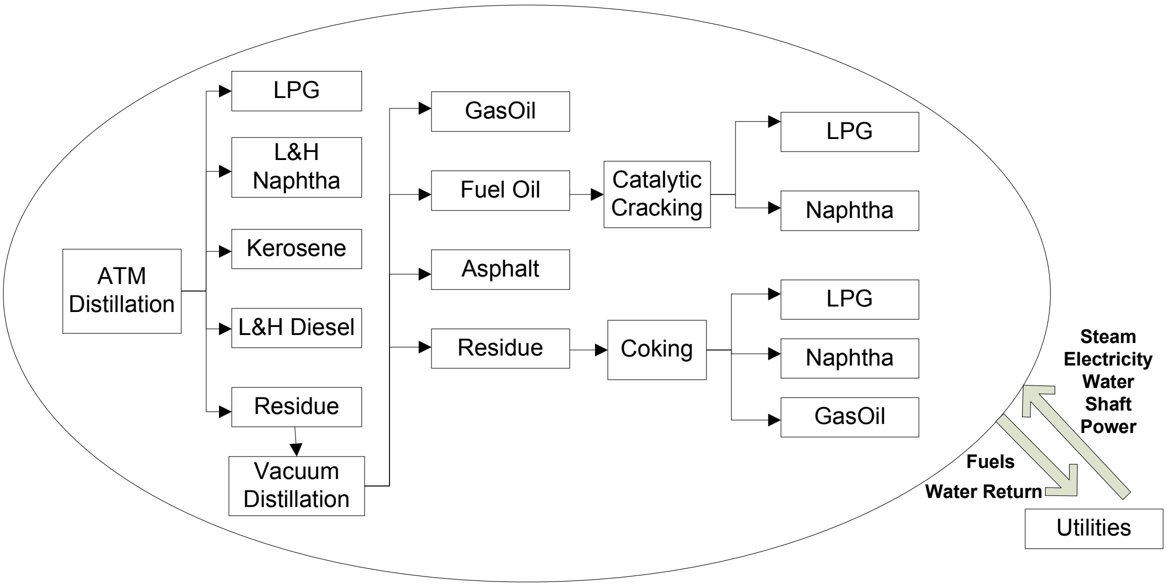

Figure 1. Simplified refining scheme of the analyzed refinery

3. UTILITIES PLANT DESCRIPTION

The utilities plant analyzed (Fig. 2) has interface with several different units of the refinery. It receives fuel gas (streams 46, 49 and 50) mainly from catalytic cracking and coking units. It also gets fuel oil (48) from distillation and high temperature CO (47) from catalytic cracking and, besides these fuels, it also makes use of natural gas imported from an outside producer (45). This natural gas is used in the gas turbine (utilities plant) and also in others auxiliary processes in the refinery such as in hydrogen production unit.

The utilities plant basically provides medium pressure (14 bar) steam for cracking, coking and distillation units, and high pressure (91 bar) and low pressure (3 bar) steam for some auxiliary units. It also provides high pressure water (120 bar) to coking and auxiliary units as well as electricity for all units of refinery. Some huge equipments such as air compressors (CP1), air blowers (CP2) and cooling tower pumps (PP1 and PP2) make use of mechanical shaft power supplied by utilities plant's turbines (54, 55, 56, 57). The boilers are fed by two different fuels and the heat recovery steam generator (B3) has a fuel gas supplementary firing. The purge of the boilers is re-expanded in a vessel down to medium pressure generating medium pressure steam (39, 41) while the condensed part of purge is used to pre-heat feed water before going to water treatment process (40, 42). Electricity is supplied by the condensing-extraction steam turbine and by the gas turbine generators. When it is required, electricity can be bought from the grid (this case was not analyzed in this paper). Condensate return from processes and condensers together with the water from water treatment process (WTP) are sent to deaerator that uses low pressure steam as energy input for the deaeration process. After that, deaerated water is compressed in a pumping station, pre-heated and then fed to the boilers.

Figure 2 presents synthesis plant of the utilities unit described above. For sake of simplicity, components and flows that have the same input, output and function are coupled. This means, for example, that where it is represented one boiler, more than one boiler, using same fuels, totaling the same capacity, are used in the real plant. The same coupling was done for the other components of the cycle. Tab. 1 shows the properties of each stream presented in Fig. 2.

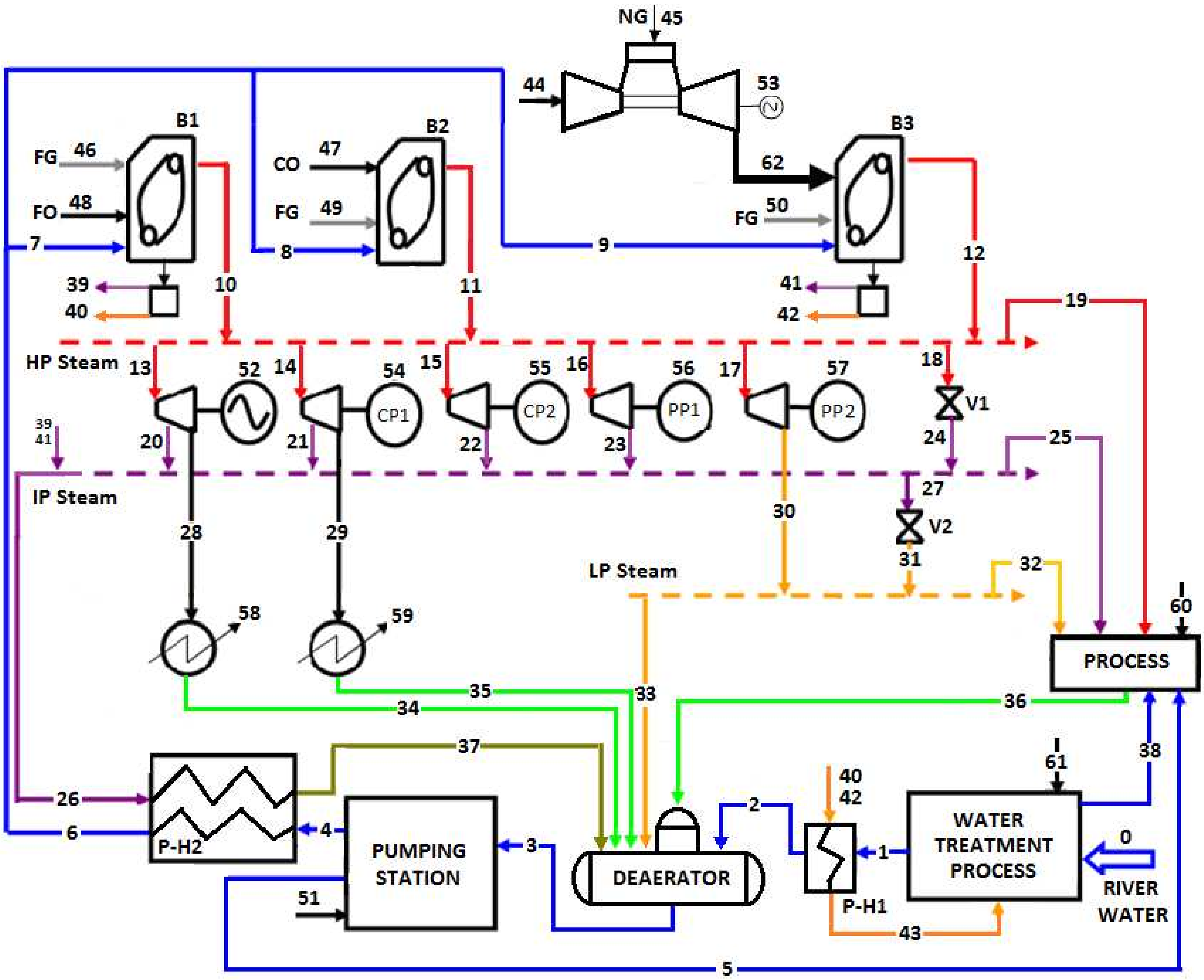

Figure 2. Simplified refinery`s utilities plant

Nomenclature:
B1, B2, B3 - Boilers
CO - Carbon Monoxide
Cond - Condenser
CP1, CP2 - Turbo-Compressors/Blowers
DEA - Deaerator
FG - Fuel Gas
FO - Fuel Oil
GT - Gas Turbine
NG - Natural Gas
P-H1, P-H2 - Pre Heaters
PP1, PP2 - Turbo-Pumps
ST - Steam Turbine
V1, V2- Valves
WTP -Water Treatment Process

4. METHODOLOGY

4.1. System Developed

The system under development gets thermodynamic data from plant`s sensors through plant information system (PI) using a Microsoft Excel Spread Sheet. Using data of mass flow, temperature, pressure and composition the necessary thermodynamic data such as enthalpy, entropy and exergy are calculated for the different flows. Thus using

PI link the energy and exergy balances are performed for any time interval required or even in real time. Before using the data provided by the system it is necessary to check mass and energy balance information once that strong transient conditions may be present, manly when short time interval or real time are used.

4.2. Exergy calculation

In order to perform an exergy analysis, the exergy of each stream depicted in fig. 2 has to be calculated. All gaseous streams whose the components are present in the environmental atmospheric air, such as flue gases, were considered as a mixture of ideal gases and have its total exergy flow (kW) calculated according to equation (1), where the term outside of square brackets is the molar flow of the mixture, the first term inside the square brackets is the chemical exergy of the mixture, the second and the third terms are the thermal exergy while the forth term is the mechanical exergy. In equation (1) P_0 means environmental pressure, T_0 means environmental temperature, x_n means the molar concentration of a n component in the mixture while $x_{n,o}$ means concentration of the component in the environment.

$$\dot{B}_{TOT} = \frac{m}{\sum x_n \cdot M_n} \cdot \left[\sum x_n \cdot \bar{R} \cdot T_0 \cdot \ln\left(\frac{x_n}{x_{n,o}}\right) + \sum x_n \int_{T_0}^{T_i} Cp_n \cdot dT - T_0 \cdot \sum x_n \int_{T_0}^{T_i} \frac{Cp_n}{T} \cdot dT + \bar{R} \cdot T_0 \cdot \ln\left(\frac{p}{p_0}\right) \right] \tag{1}$$

The chemical exergy of the gaseous fuels, whose components are not present in the environmental atmosphere, (fuel gas, CO gas and natural gas) was obtained using the standard chemical exergy provided by Szargut *et al.*, (1988), the physical components of these fuels were calculated as in second, third and fourth term of equation (1). The chemical exergy of liquid fuels (fuel oil) was calculated according to Szargut and Styrylska *apud* Kotas (1985), by the product of the fuel lower heating value (LHV) and a given factor φ defined by equation (2), where H, O, S and C are the are the mass fractions of the respective chemical element present in the fuel.

$$\varphi = 1.0401 + 0.1728 \cdot \frac{H}{C} + 0.0432 \cdot \frac{O}{C} + 0.2169 \cdot \frac{S}{C} \cdot \left(1 - 2.0628 \cdot \frac{H}{C}\right) \tag{2}$$

For water and steam the flow of physical exergy was calculated by equation (3) whilst its chemical exergy was considered as 0.9 kJ/kmol as in Szargut *et al*, (1988). The specific enthalpy and entropy for water was calculated using X Steam macros for Excel that uses IF-97 Steam Tables.

$$\dot{B}_{Ph} = \dot{m}\left[\left(h - h_0\right) - T_0\left(s - s_0\right)\right] \tag{3}$$

For equations (1), (3) the reference temperature and pressure used was 25ºC and 101.325 kPa respectively. After calculated all exergy flows, the exergy efficiency for each equipment, exergy destruction in each piece of equipment and the exergy balance for the whole plant can be performed.

4.3. Condensing to power approach

In order to define the exergy efficiency of the cycle`s condensers, the condenser to power approach was used. In most exergy or exergoeconomic methodologies, the condenser is aggregated to the steam turbine since the function of a condenser cannot be to remove exergy from a stream without getting a thermodynamic gain out of this removal, thus it was not possible to calculate the condenser efficiency singly. Some methodologies make use of negentropy and sintropy flows in order to calculated the product of the condenser as in Frangopoulos (1987) and Santos *et al.* (2009), however, by using negentropy or sintropy flows the complexity of the analysis is substantially increased and a productive structure of the cycle is required to clear up the costing equations used.

The condensing to power approach considers that the electricity generated by the steam turbine from atmospheric pressure down to condensing pressure is due to the condenser, even though it is generated in the steam turbine, such as indicated by the arrow in fig. 3. Thus, by using this approach, it is possible to evaluate the exergy efficiency of the condensers without a productive structure and negentropy flows such as in Frangopoulos (1987) or in the method proposed by Santos *et al.* (2009).

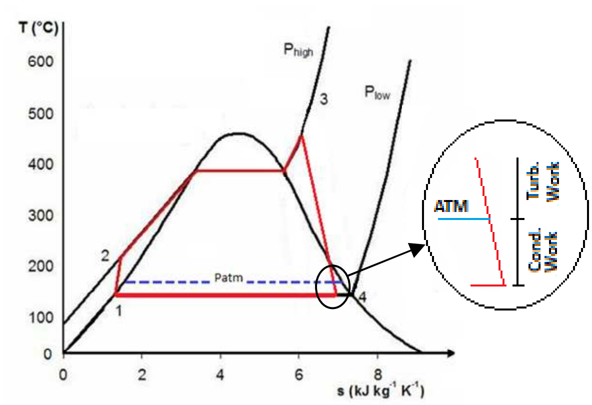

Figure 3. Condenser product in the Condensing to Power approach

The condensing to power method provides the same unit exergy costs, quantity of exergy spent to produce an exergy product unit, for all product of a given cycle as obtained using methods that aggregate the condenser to the steam turbine as showed by Mendes da Silva *et al.*,(2010). This happens because in both cases all the costs regarding the condensing system are directly allocated to the electricity.

4.4. Exergoeconomic approach

In this application the unit exergy cost of each real stream (physical structure) is evaluated. This evaluation provides information about how much exergy is necessary to produce one unit of exergy of a given flow. The total exergy cost is also evaluated providing the information about how the fuel exergy is split in each stream of the utilities plant. Both, unit exergy cost and total exergy cost are shown in table 1. In order to perform these evaluation, the unit exergy cost of the fuels were considered equal to one (external to the plant), however the future goal of the ongoing project is to evaluate these cost considering the processes in which the fuels came from and also using the monetary operation costs.

In order to have an equal number for variables and equations some auxiliary equations are needed. These auxiliary equations were obtained considering the extractions, back pressure, condensed steam, valves output flow and process return has the same unit exergy cost of the input flow. This is equivalent to the fuel (F) principle that considers that these components only make use of part of the exergy present in their input flow (Fuel), therefore the exergy remaining in the output flow has the same unit exergy cost of the input. Thus, the unit exergy cost of an extraction or back pressure flow of a steam turbine should be equal to that of its input flow. The fuel principle was stated by Tsatsaronis and Lazzaretto, (2002).

5. RESULTS

Figure 4 presents energy and exergy efficiencies for the different components of the plant analyzed. It can be seen that the energy efficiency of the equipment that provide shaft power (CP1, CP2, PP1 and PP2) were considered to be 100% (no losses in transmission and rotor), while their exergy efficiency are, in most of cases, smaller than 90%. It also can be seen a high difference between the energy and exergy efficiency for the boilers, it happens because the increase of enthalpy in the water is much greater than the increase of exergy, both increases provided by the energy and exergy of the fuels that are very close, usually 4% of difference between exergy and enthalpy for gaseous fuels and 4% to 8% for liquid fuels (Kotas, 1985). The highest difference between exergy and energy efficiency happens in the pre-heater 1 (P-H1) since flows 40 and 42 have a very small mass flow in comparison with flow 1, thus, the hot stream loses all its thermal exergy while the temperature of the cold stream is increased only by 2.64 ºC, this implies a very small increase in the exergy of the cold stream.

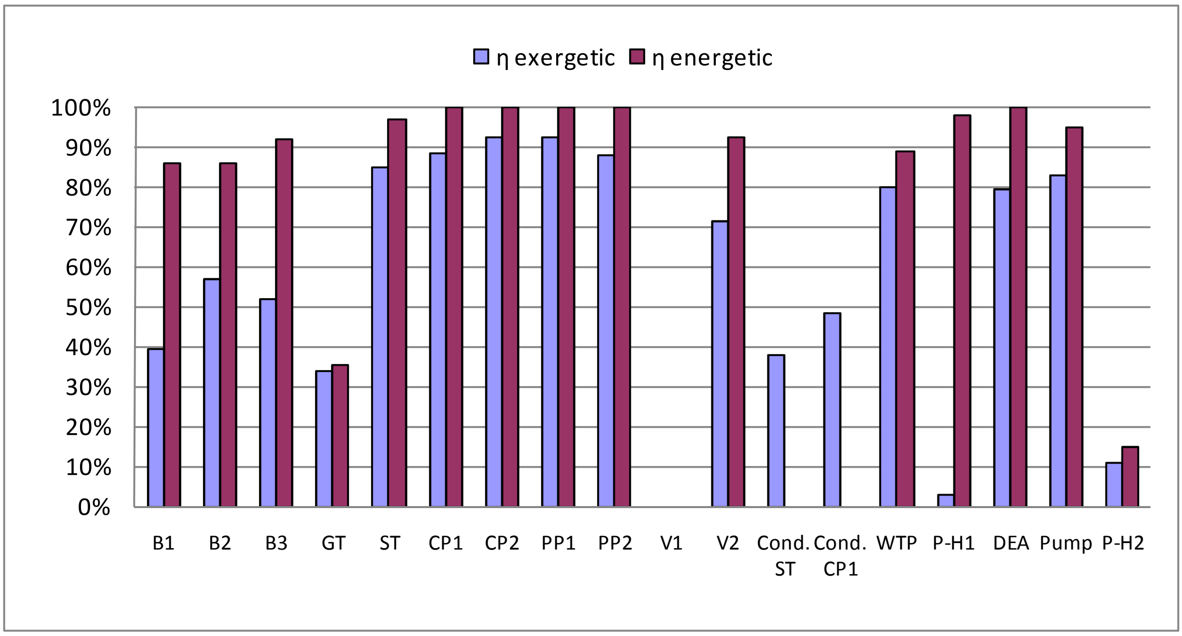

Figure 4. Energy and Exergy efficiencies of the equipment present in the utilities plant

Figure 5 shows the exergy destruction in each component of the utilities plant. It is important to note that equipment where a combustion process takes place, such as boilers (B1,2,3) and gas turbine (GT), and equipments where there is heat transfer under high temperature differences, such as boilers and pre-heater 2 (P-H2), are the main responsible for the most of exergy destroyed in the plant. The boilers and gas turbine together are responsible for 80% of total exergy destruction, which is similar to the results found by Rivero and Hernández in which the boiler represents almost 91% of total exergy destroyed in a 150.000 bpd refinery utilities plant where no gas turbines are present. According to Rivero and Hernández (1995) the utilities plant is responsible for 40% of the exergy destruction in a refinery. So, as an estimation, boilers and gas turbine are responsible for 32% of the exergy destroyed in the overall refining process for the analyzed refinery. It can also be seen that through the condenser to power method it is possible to evaluate the exergy efficiency of condenser and also the exergy destruction in these components.

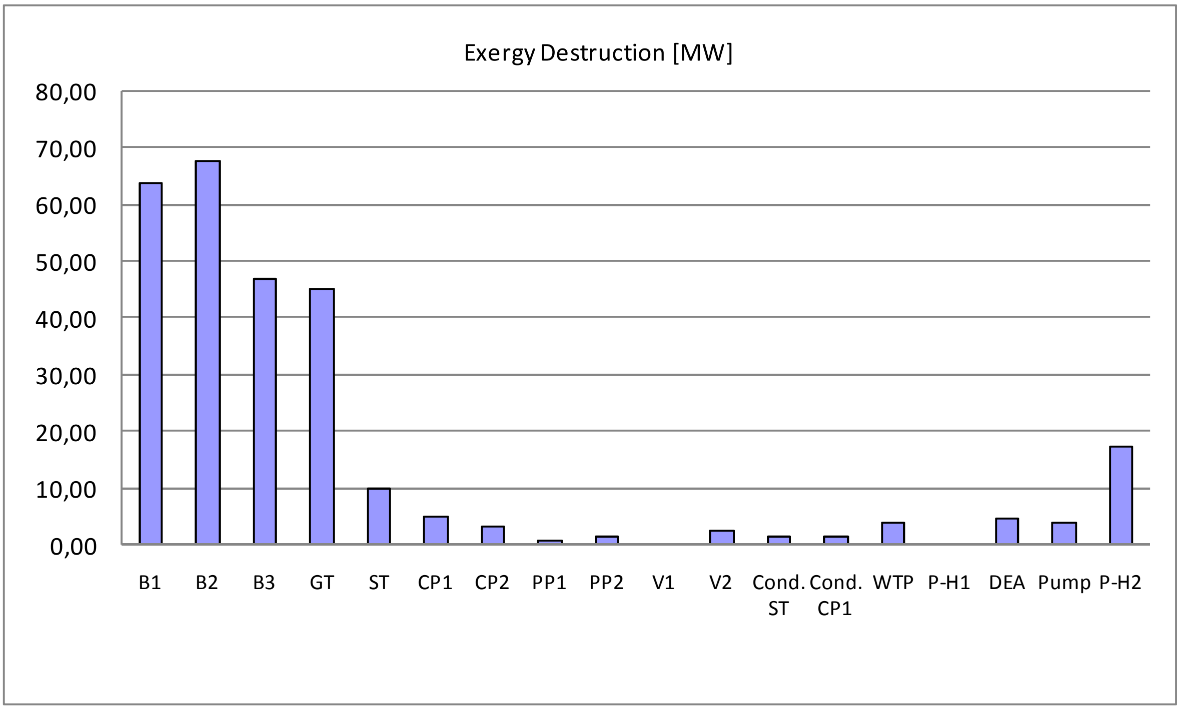

Figure 5. Exergy destruction in each equipments presents in the utilities plant

The analyzed utilities plant has an overall exergy efficiency of 35% and it is responsible for the destruction of more than 280 MW of exergy (exergy losses included). The Grassmann diagram of the plant can be seen in fig. 6. It clearly shows how much of the exergy present in the fuels supplied to the utilities plant is used in the desired products.

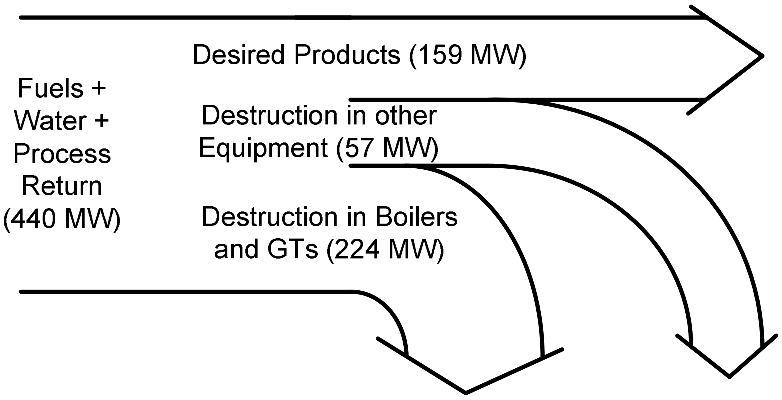

Figure 6. Grassmann diagram showing the exergy destruction in the utilities plant

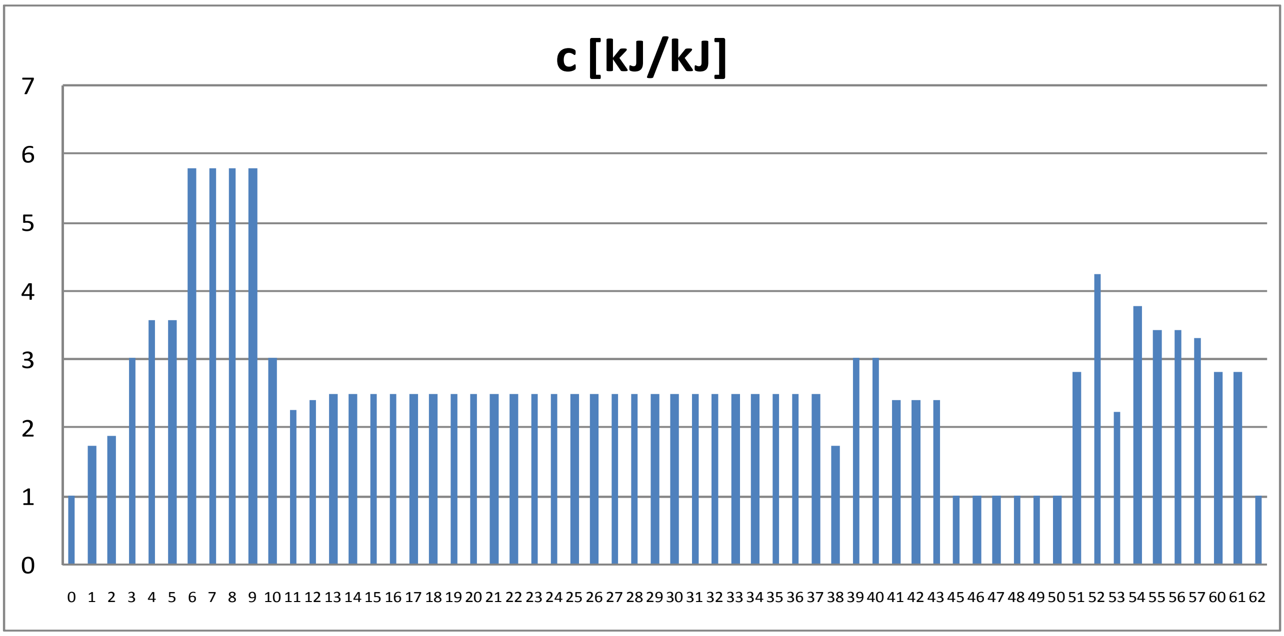

Figure 7. Exergy unit cost of each stream present in fig. 2

Figure 7 shows how much exergy was necessary to generate one unit of exergy of each given stream in fig. 2. It can be seen the feed water, streams (6, 7, 8, 9) have the highest unit exergy cost followed by the electricity generated by steam turbine (52) and by shaft power generated by the components that make use of high pressure steam (54, 55, 56 and 57). It also can be observed that the unit exergy cost of the fuels is considered to be equal to one (45, 46, 47, 48, 49, 50). Besides that, it was possible to calculate the unit exergy cost of the steam at high, intermediary and low pressure (13 to 32) that is 2.47 kJ/kJ, electricity (51, 60 and 61) that is 2.81 kJ/kJ, high pressure water (5) that is 3.57 kJ/kJ and low pressure water (38) that is 1.73 kJ/kJ that are the flows exported by utilities plant.

6. CONCLUSION

The utilities plant of a refinery was analyzed through an exergy analysis using a simple and effective way to define and analyze the condensers present in the plant without the use of negentropy. The exergy analyzes shows that the boilers followed by gas turbine are the components responsible for the greatest part of the exergy destroyed (80%), approximately 224 MW, while only 53,7 MW of electricity is been generated. The work also shows that the heat exchanger (P-H1) has a very small exergy efficiency since it operates under high temperature differences. Using exergoeconomic analyzes it was possible to evaluate in terms of unit exergy cost each stream leaving the utilities plant and getting into refining process such as: electric power, steam, shaft power and water.

7. ACKNOWLEDGEMENTS

The first and last authors of this paper would like to thank CNPq and Petrobras for the financial support.

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9. RESPONSIBILITY NOTICE

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Table 1. Properties and quantities of the streams presented in fig.2.

STREAM	m [kg/s]	T[ºC]	P [bar]	h [kJ/kg]	H [kJ/s]	s[kJ/kgºC]	S [kJ/ºCs]	b[kJ/kg]	B [kW]	c [kJ/kJ]	C[kJ/s]
0	303,731	25,000	1,000	104,928	31.869,875	0,367	111,539	50,000	15.186,535	1,000	15.186,535
1	73,577	25,000	4,000	105,206	7.740,702	0,367	27,020	50,278	3.699,276	1,734	6.416,301
2	73,577	27,642	4,000	116,251	8.553,380	0,404	29,728	50,350	3.704,552	1,876	6.949,643
3	159,059	130,859	3,211	550,086	87.496,286	1,644	261,439	114,591	18.226,731	3,004	54.746,770
4	128,645	130,859	119,796	557,998	71.783,409	1,632	210,006	125,845	16.189,255	3,572	57.823,043
5	30,414	130,859	119,796	557,998	16.971,218	1,632	49,650	125,845	3.827,505	3,572	13.670,672
6	128,645	145,189	119,796	618,891	79.616,999	1,781	229,059	142,580	18.342,097	5,790	106.191,856
7	30,063	145,189	119,796	618,891	18.605,874	1,781	53,529	142,580	4.286,405	5,790	24.816,212
8	62,103	145,189	119,796	618,891	38.435,151	1,781	110,578	142,580	8.854,658	5,790	51.264,178
9	36,478	145,189	119,796	618,891	22.575,974	1,781	64,951	142,580	5.201,034	5,790	30.111,466
10	29,230	475,544	90,970	3.323,533	97.146,605	6,572	192,090	1.418,741	41.469,692	3,009	124.802,551
11	62,103	475,544	90,970	3.323,533	206.402,282	6,572	408,124	1.418,741	88.108,473	2,251	198.321,508
12	35,645	475,544	90,970	3.323,533	118.466,611	6,572	234,247	1.418,741	50.570,721	2,406	121.663,385
13	46,926	475,544	90,970	3.323,533	155.960,616	6,572	308,385	1.418,741	66.576,065	2,469	164.376,247
14	31,788	475,544	90,970	3.323,533	105.648,980	6,572	208,902	1.418,741	45.099,164	2,469	111.349,796
15	31,355	475,544	90,970	3.323,533	104.209,283	6,572	206,056	1.418,741	44.484,590	2,469	109.832,413
16	6,521	475,544	90,970	3.323,533	21.672,229	6,572	42,853	1.418,741	9.251,385	2,469	22.841,662
17	8,329	475,544	90,970	3.323,533	27.682,141	6,572	54,737	1.418,741	11.816,881	2,469	29.175,869
18	0,000	475,544	90,970	3.323,533	0,000	6,572	0,000	1.418,741	0,000	2,469	0,000
19	2,059	475,544	90,970	3.323,533	6.842,249	6,572	13,529	1.418,741	2.920,802	2,469	7.211,457
20	37,744	293,540	14,142	3.026,301	114.225,133	6,925	261,381	1.016,153	38.353,832	2,469	94.695,579
21	19,787	293,540	14,142	3.026,301	59.882,537	6,925	137,029	1.016,153	20.107,000	2,469	49.644,166
22	31,355	293,540	14,142	3.026,301	94.889,589	6,925	217,135	1.016,153	31.861,459	2,469	78.665,914
23	6,521	293,540	14,142	3.026,301	19.734,028	6,925	45,157	1.016,153	6.626,174	2,469	16.360,018
24	0,000	293,540	14,142	3.026,301	0,000	6,925	0,000	1.016,153	0,000	2,469	0,000
25	64,488	293,540	14,142	3.026,301	195.159,075	6,925	446,582	1.016,153	65.529,347	2,469	161.791,902
26	23,019	293,540	14,142	3.026,301	69.663,203	6,925	159,410	1.016,153	23.391,094	2,469	57.752,590
27	8,734	293,540	14,142	3.026,301	26.430,926	6,925	60,482	1.016,153	8.874,818	2,469	21.911,919
28	9,182	67,225	0,276	2.340,431	21.489,871	6,970	64,001	316,799	2.908,852	2,469	7.181,952
29	12,001	68,928	0,298	2.288,806	27.467,478	6,789	81,477	319,126	3.829,769	2,469	9.455,695
30	8,329	165,000	3,211	2.791,737	23.252,739	7,119	59,299	723,644	6.027,328	2,469	14.881,467
31	8,734	165,000	3,211	2.791,737	24.382,300	7,119	62,179	723,644	6.320,120	2,469	15.604,372
32	0,000	165,000	3,211	2.791,737	0,000	7,119	0,000	723,644	0,000	2,469	0,000
33	17,063	165,000	3,211	2.791,737	47.635,039	7,119	121,478	723,644	12.347,448	2,469	30.485,838
34	9,182	48,603	4,000	203,791	1.871,208	0,686	6,294	53,967	495,527	2,469	1.223,457
35	12,001	59,210	4,000	248,150	2.977,994	0,821	9,854	57,906	694,921	2,469	1.715,760
36	24,218	99,000	4,000	415,108	10.052,882	1,295	31,373	83,426	2.020,371	2,469	4.988,294
37	23,019	169,738	14,142	718,403	16.537,100	2,039	46,931	165,107	3.800,640	2,469	9.383,777
38	231,404	25,000	4,000	105,206	24.345,058	0,367	84,961	50,301	11.639,821	1,734	20.188,977
39	0,208	195,519	14,142	2.789,209	581,085	6,464	1,347	916,542	190,946	3,009	574,650
40	0,625	195,519	14,142	832,245	520,153	2,288	1,430	204,533	127,833	3,009	384,712
41	0,208	195,519	14,142	2.789,209	581,085	6,464	1,347	916,548	190,947	2,406	459,383
42	0,625	195,519	14,142	832,245	520,153	2,288	1,430	204,533	127,833	2,406	307,541
43	1,250	40,000	14,142	168,788	210,984	0,572	0,715	52,842	66,053	2,406	158,911
44	111,648	25,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
45	2,235	19,894	39,300	47.796,510	106.838,335	-	-	49.719,895	111.137,629	1,000	111.137,629
46	0,589	24,011	4,723	46.300,000	27.263,638	-	-	48.295,430	28.438,642	1,000	28.438,642
47	109,210	587,967	1,014	1.529,554	167.042,442	-	-	1.009,216	110.216,343	1,000	110.216,343
48	1,675	25,000	1,000	40.337,000	67.558,632	-	-	43.291,541	72.507,059	1,000	72.507,059
49	0,763	24,011	4,723	46.300,000	35.318,822	-	-	48.295,430	36.840,987	1,000	36.840,987
50	1,322	24,011	4,723	46.300,000	61.213,866	-	-	48.295,430	63.852,052	1,000	63.852,052
51	-	-	-	-	-	-	-	-	5.951,062	2,814	16.746,945
52	-	-	-	-	-	-	-	-	16.182,879	4,230	68.457,212
53	-	-	-	-	-	-	-	-	37.520,794	2,203	82.670,837
54	-	-	-	-	-	-	-	-	15.885,881	3,776	59.989,870
55	-	-	-	-	-	-	-	-	9.106,827	3,422	31.166,499
56	-	-	-	-	-	-	-	-	1.893,931	3,422	6.481,644
57	-	-	-	-	-	-	-	-	4.328,232	3,303	14.294,402
58	-	-	-	-	19.618,663	-	-	-	-	-	-
59	-	-	-	-	24.489,483	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	39.553,962	2,814	111.309,205
61	-	-	-	-	-	-	-	-	4.001,206	2,814	11.259,833
62	113,883	533,043	1,017	396,165	45.116,544	-	-	249,965	28.466,792	1,000	28.466,792